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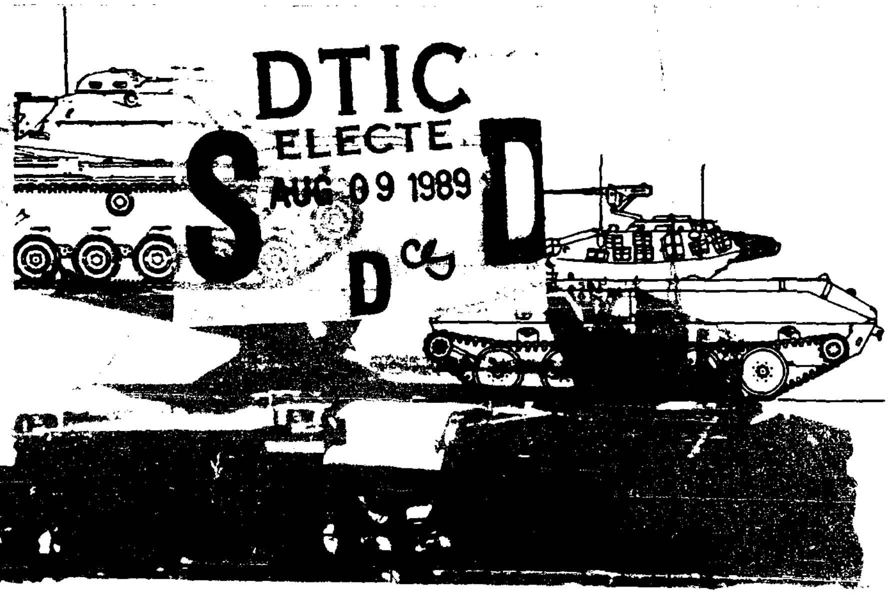

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Armored Combat Vehicle Vulnerability to Anti-armor Weapons:

A Review of the Army's Assessment Methodology

Committee on a Review of Army Vulnerability Assessment Methods
Board on Army Science and Technology
Commission on Engineering and Technical Systems
National Research Council

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Preface

An important element to be considered in the design and development of a military system is its vulnerability, i.e., the degree to which its performance is degraded by exposure to enemy weaponry. Specifically, in the case of an armored combat vehicle, such as an M1 Abrams Tank or an M2/M3 Bradley Fighting Vehicle, vulnerability assessment is concerned with the degree to which the vehicle and its crew are able to function after being struck by enemy fire. Live-fire tests of components, subsystems, and full-scale vehicles have become an important factor in the difficult, complex task of making this assessment.

In view of the complexities, it is not surprising that differences of opinion have arisen regarding the role of live-fire testing and the interpretation of test results in assessing the vulnerability of armored combat vehicles. Walter W. Hollis, Deputy Under Secretary of the Army (Operations Research), requested the assistance of the National Research Council's Board on Army Science and Technology to help resolve these differences. The Committee on a Review of Army Vulnerability Assessment Methods was accordingly established. Its task was to (1) help define the objectives of the Army's armored vehicle vulnerability assessment program, (2) consider the proper balance of computer modeling and live-fire testing in the program, (3) identify any technical deficiencies that might exist in the assessment process, and (4) suggest improvements in the program as appropriate.

This report is the result of the deliberations of the committee, which were conducted over almost the entire 1988 calendar year. The initial meetings of the committee were held successively at the Ballistic Research Laboratory (Aberdeen Proving Ground, Maryland), the U.S. Army Tank-

Automotive Command (Warren, Michigan), and the U.S. Army Armor Center and Fort Knox (Fort Knox, Kentucky). At each of these installations the committee received a series of briefings presenting the current points of view of the science and engineering research community, the design, development, and acquisition community, and the user community, respectively. These briefings dealt with issues of combat vehicle vulnerability assessment and live-fire testing relevant to the committee's interests and responsibilities. The remainder of the committee's meetings—four in number—were held at the National Research Council in Washington, D.C., to review and assimilate the information at the committee's disposal, to discuss and formulate its conclusions and recommendations, and to prepare and revise its report.

The individuals who contributed in a variety of ways to the work of the committee during the course of its study are too numerous to be listed separately here. However, in addition to the initial guidance provided by Mr. Hollis, the Committee would like to acknowledge with gratitude the assistance received from the Ballistic Research Laboratory through D. L. Rigotti, Chief, Vulnerability/Lethality Division, and members of his staff, and through Dr. C. W. Kitchens, Chief, Terminal Ballistics Division, and members of his staff; from the Tank-Automotive Command through Major General W. S. Flynn, Commanding General, and through G. Orlicki, Deputy for Research, Development and Engineering, and members of his staff; from Brigadier General P. McVey, Program Executive Officer, Close Combat Vehicles; and from the Army Armor Center and Fort Knox through Colonel D. L. Smart, Director, Directorate of Combat Developments, and members of his staff.

The committee also wishes to thank the staff of the Board on Army Science and Technology for excellent support provided throughout the study.

Martin Goland, Chairman
Committee on a Review of Army
Vulnerability Assessment Methods

Contents

Executive Summary

As part of the final acceptance program leading to full-scale production of a new combat vehicle, Congress has mandated the conduct of live-fire tests against fully combat-loaded prototypes. The basic intent of the tests is to provide insight into the vulnerability of the vehicle, i.e., the extent to which the vehicle and its crew are susceptible to the damaging effects of enemy fire. However, the precise purpose of such tests, their experimental design, and the significance of the results have been the source of differences of opinion.

Accordingly, the National Research Council, through its Board on Army Science and Technology, was requested by the Army to clarify the relevant issues and recommend guidelines for the conduct of combat-loaded, live-fire tests. The board was also asked to review the adequacy of the methodology currently employed for estimating vehicle vulnerability and to suggest improvements as deemed appropriate.

The report makes clear that the principal role of combat-loaded, live-fire testing is to provide an independent check on the general success of the design and development process for the vehicle. Such tests do *not* contribute significantly to the assessment of vulnerability in the form needed to support subsequent survivability estimates and other necessary Army uses. The quantity of data gathered during the tests is too limited in scope to be statistically significant. The results of combat-loaded, live-fire tests should not, therefore, by themselves be construed as a basis for approval or disapproval of the transition to full-scale production. Many additional factors must be taken into account in arriving at this decision.

Experience indicates, however, that the tests may uncover vulnerabilities not adequately considered during the design process, or may reveal an error in the more detailed assessment of vulnerability. In addition, combat-loaded live-fire tests are conducted in an environment of high visibility, providing motivation to ensure that vulnerability considerations are given adequate attention throughout the design process. Moreover, the tests are intended to include an updated roster of enemy threat weapons, some of which may have emerged since the original specifications for the vehicle were established. These various factors support the committee's conclusion that live firings against combat-loaded vehicles are a valuable adjunct to ensuring that a new vehicle meets its battlefield requirements.

It should be noted, however, that during development and engineering a large number of live firings will have been conducted against components, subsystems, and full-scale vehicles (not necessarily combat-loaded). These tests are for the purpose of gathering *engineering* information and serve a different purpose than the congressionally mandated tests, which are planned and conducted independently of the design team. Moreover, the basis for the choice of shotlines (firing trajectories) chosen for the mandated series should be random selection, uninfluenced by engineering considerations.

Recommended procedures for designing the combat-loaded, live-fire test series are contained in the report, along with suggestions for their execution. The committee believes that a minimum of three shots should be fired for each selected weapon-warhead combination and that the estimated cost per firing based on recent experience can be reduced in the future, particularly if an adequate program of engineering test firings has already been completed during the development process.

The discussion in the report emphasizes that arriving at vulnerability assessments in the form needed for Army engineering and planning purposes is a complex task that depends on the use of analytic models programmed for execution on high-speed computers. Such an assessment entails, for each combination of weapon and warhead constituting a battlefield threat, an analysis of the damage due to attack from all directions and at all ranges. Thus, the effects of thousands of shotlines must be predicted in order to arrive at an adequate picture of how well enemy fire can be tolerated. The analytic models are heavily dependent for their accuracy on the results of empirical engineering test firings with live ammunition, and the committee finds this to be an area that in recent years has been starved for resources and is in an entirely unsatisfactory state. The inadequacy of this experimental data base is the largest single deficiency

Keywords; armored vehicle; survivability; (KT)

contributing to the current uncertainty in vulnerability estimates; hence, the issue is an important one.

The analytic models currently in use by the Army are reviewed in detail, and suggestions are advanced which, in the committee's opinion, will lead to improved models that offer the best achievable accuracy for a given expenditure of calculational time and computer resources.

1
Introduction

PURPOSE OF STUDY

It is vital to the success of any armored combat mission that the capabilities and limitations of the arms and equipment be well understood. A knowledge of the vulnerability of an armored vehicle and its crew to an expected enemy weaponry threat is an essential element in the commander's battle plan. For the vehicle to be effective, a reasonable invulnerability to a variety of expected enemy threats must be designed into the vehicle. An important element is some form of protective armor. Assessing the effectiveness of armor and armor configurations (vulnerability analysis) is a complicated process that begins in the conceptual design phase and ends with a final series of tests using live ammunition against a fully loaded, combat-ready vehicle. The results of these tests and their interpretation are crucial to the decision to deploy the vehicle.

During the combat-loaded, live-fire testing of the Bradley Fighting Vehicle System (BFVs)[1] in 1986, differences of viewpoint arose among the Office of the Secretary of the Army, the Office of the Secretary of Defense, and the Congress regarding the role and conduct of live-ammunition firings and the interpretation of results in assessing the vulnerability of armored vehicles. To resolve these differences, the National Research Council's Board on Army Science and Technology was requested by Walter W. Hollis,

[1] There are two versions of the BFVs—the M2 Infantry Fighting Vehicle (IFV) and the M3 Cavalry Fighting Vehicle (CFV).

cont'd

Deputy Under Secretary of the Army (Operations Research), to examine and make recommendations concerning the Army's assessment of vulnerability of armored vehicles against anti-armor weapons. Accordingly, a Committee on a Review of Army Vulnerability Assessment Methods was formed to conduct the necessary studies. The membership of the committee is listed on page iii.

The terms of reference for the study are as follows:

- address issues that will help the Army define the objectives of its armored vehicle vulnerability assessment program,
- define and analyze alternative ways to balance the use of modeling (computation) and live-fire testing to obtain findings and draw conclusions about armored vehicle vulnerability,
- identify technical deficiencies in the vulnerability assessment process where they exist, and
- suggest alternatives for improvement as appropriate.

(The Statement of Task from which the terms of reference are taken is given in Appendix A.)

VULNERABILITY

It became evident in early deliberations by the committee that a thorough and proper appraisal of the role of final live-fire tests against full-scale, combat-loaded armored vehicles could be made only after an in-depth understanding had been achieved of how vulnerability considerations are introduced during the development phase of the vehicle (from conceptual design to prototype fabrication). To determine the sequence of steps involved in the process and the relationship of these steps, it was necessary to gather information from relevant government agencies. Accordingly, the schedule of visits and related contacts listed in Appendix B was undertaken. It should be noted that the activities visited or contacted include:

- the U.S. Army Armor Center and School (USAACS) of the U.S. Army Training and Doctrine Command (TRADOC), concerned with concept formulation and preparation of the Required Operational Capability (ROC);
- the U.S. Army Tank-Automotive Command (TACOM) of the U.S. Army Materiel Command (AMC), responsible for armored vehicle design, development, and manufacturing;

• the AMC Ballistic Research Laboratory (BRL), the Army's technical center for ballistics, weapons effects, and armor protection;

• the U.S. Army Test and Evaluation Command (TECOM), the independent test and evaluation agency for the Army Materiel Command;

• the U.S. Army Materiel Systems Analysis Agency (AMSAA), responsible for AMC systems analysis of the effectiveness of weapons and vehicles;

• the Program Executive Officer for Close Combat Vehicles (PEO-CCV), responsible for armored combat vehicle programs; and

• the U.S. Army Operational Test and Evaluation Agency (OTEA), concerned with formulating and supervising operational tests for evaluation of armored vehicles.

Since this study is concerned with the *vulnerability* of armored vehicles against anti-armor weapons rather than the *survivability* of armored vehicles, the distinction between the two should be made.

• Vulnerability, the concern of this study, refers only to the ability of an armored combat vehicle and its crew to withstand the damaging effects of an anti-armor weapon. Stated differently, vulnerability assessment relates to determining the ability of the armored combat vehicle and its crew to function after being struck by enemy fire.

• Survivability, on the other hand, is concerned with the capability of the crew and vehicle to complete their mission taking into account such factors as likelihood of engagement, battlefield environment, tactics employed, crew training status, and vehicle performance, in addition to vulnerability to enemy firepower.

Damage assessments in a relatively gross sense are usually rated in terms of M-kill (loss of mobility), F-kill (loss of firepower), and K-kill (catastrophic loss of vehicle and crew). Numerical ratings in these categories of damage, ranging from 0 (not significant) to 1 (total loss), represent a more sophisticated approach to vulnerability assessment, but also reveal the complications standing in the way of accurate evaluations. It will be immediately recognized that, for each threat weapon to be considered, the point of attack may be almost anywhere on the surface of the target vehicle. The direction of attack may be at almost any azimuth and a variety of elevation angles. However, after taking into account various battle scenarios and terrain configurations, some attacks among the large number of possibilities are clearly more likely than others. The range at which the weapon is fired, which determines the striking velocity of the round, is another factor that must be taken into consideration. This is of particular importance for projectiles which depend on kinetic energy for their effect. For attacks powerful enough to penetrate the hull and enter interior compartments of the vehicle, significant damage will be stochastic (probabilistic) in character; for example, the lethal effects of spall fragments inside the vehicle will not be the same even for two attacks seemingly identical in other respects.

Thus, it is seen that vulnerability assessment for combat vehicles, even if all the required data were available, is a most complex issue. Statements such as "the probability of kill of vehicle X by weapon Y is 0.56" represent a spatial- and event-average of all conceivable attacks, and do not represent the result of any particular engagement.

Despite the difficulty, it is necessary that reasonably accurate estimates of vulnerability be obtained. The estimates usually are in the form of tabular data (or computer algorithms) that describe the damage due to attack by weapon-warhead combinations on the vehicle envelope; such data are used in many subsequent analyses of considerable importance to Army planning.

For example, in computerized war gaming, or in the interpretation of field exercises, the damage to a vehicle caused by an impacting weapon is assessed by reference to vulnerability tables. War games, in turn, can change concepts regarding the tactics (doctrine) describing the role and use of the vehicle in battle. Attrition analyses of materiel, which enter into procurement decisions, also flow from studies in which vulnerability considerations play an important part. Finally, the answer to the important issue of crew protection and survivability requires a thorough understanding of the vehicle vulnerability.

To characterize the vulnerability of the vehicle to a particular munition, the previously described elements must be interrelated in order to model damage events over a wide range of values of the various parameters. Concurrent with the modeling of the vulnerability of the vehicle, experimental programs in impact phenomenology are needed to determine the damage mechanisms and the distribution and effect of spall and projectile fragments on various components and subsystems of the vehicle. As the development of the vehicle proceeds, the experiments become more complex. Tests must be performed using various munitions against components, subsystems, and systems. These experiments are the check points used to to verify current design configurations or to form the basis for design changes. The final step in the process leading to full-scale production is combat-loaded, live-fire testing.

STUDY APPROACH

With this approach to vulnerability analysis as background, the committee focused its attention on these two areas of investigation:

1. how the Army should use modeling and experimentation to complement each other in the design, development, and product improvement of a vehicle intended to withstand attack by enemy anti-armor weapons;
2. how live-fire tests of a full-scale, combat-loaded vehicle should be conducted and what is their role in the process of evaluating vehicle vulnerability.

In the following sections, each of these is examined and discussed, and recommendations are made where appropriate.

2
Vulnerability Considerations During Concept Formulation and Vehicle Design

To appreciate the role of full-scale, combat-loaded, live-fire tests in vulnerability assessment, it is necessary to understand how issues of vulnerability are dealt with throughout the process by which the configuration of fielded equipment is reached.

REQUIRED OPERATIONAL CAPABILITIES

The formal requirement for a new combat vehicle originates with a document called the Required Operational Capability (ROC) prepared by TRADOC. During the deliberations that lead to the issuance of the ROC, considerable interchange of ideas and data takes place between personnel of the developer (AMC-TACOM), the user (TRADOC-Armor Center and School), other Army agencies, intelligence sources, industry, and various other groups including the field forces. Factors considered in evaluating various vehicle concepts and their desirable performance features include: threat definition; computer simulations of force-on-force battle scenarios; war games conducted in the field; experiences gathered during past conflicts in which U.S. or friendly forces were involved; an accommodation between ideal goals (such as infinite agility, zero vulnerability, and extreme lethality) and what is anticipated to be realizable in engineering terms; cost considerations; the judgment of Army experts; and industry input.

The final requirements reflected in the ROC represent a compromise among a variety of features. A high degree of protection against enemy fire requires a heavily armored vehicle, but the associated vehicle weight results in lessened agility. A more powerful gun increases firepower, but may also add weight. Similarly, larger caliber ammunition will force a choice between increased stowage space or fewer stowed rounds. A higher system profile will increase vulnerability, but may be necessary to preserve some element of comfort to the crew or to provide necessary internal volume for ammunition, fuel storage, and other equipment. Funding constraints may also impose limits on what can be included in the overall design. These are but a few of the compromises which must be struck in arriving at the final ROC.

One aspect of the preparation of a ROC requires comment. A ROC must be prepared based on intelligence estimates of future threats made at the start of the vehicle's conceptual studies. The fielded vehicle emerges between one and two decades later. By this time the threats will have changed and may have become more severe or different in type. The dilemma in developing the ROC is that overestimation of the future threat imposes more stringent requirements on the vehicle and distorts trade-off assessments, resulting in performance requirements difficult to attain within available technology. On the other hand, underestimation will result in a vehicle unprepared for the battlefield.

Threat projections have, in most cases, not adequately estimated the newer capabilities fielded by our potential enemies. There is no reason to believe that it will ever be possible to accurately forecast the evolution of the threat over the fielded lifetime of an armored vehicle. Also, armor technology will rapidly evolve during the same time period. A practical way to deal with this situation is to specify a design approach that will facilitate the ability to make armor changes in vital areas to increase the original level of protection in response to changes in the threat.

The committee therefore believes that future ROCs can be improved by adding the requirement that technology growth be included in the design consideration.

Another factor not normally included in the ROC is the degree of attention and emphasis that should be given to the reduction of internal damage caused by penetrating rounds. In the design of military aircraft, a manual of "good design practices" has been developed over the years. The committee strongly suggests that a manual of this kind be developed for combat vehicles, that it be applied to all future designs, and that retrofits to bring fielded designs in accordance with the manual guidance be made as expeditiously as possible.

THE DESIGN PROCESS

Following the establishment and approval of the ROC, design can begin under the direction of the Project Manager, supported by TACOM, BRL, and such other agencies as may be required. A process of conceptual refinement is undertaken, with early concepts rejected in favor of other designs until a configuration is defined which appears to be closest to the optimum achievable in practice. Each concept takes into account the capability of the vehicle to resist enemy fire as prescribed in the ROC. During this phase of the design process, simplified vulnerability calculations are used which are not unduly time- and cost-consuming. The techniques employed are not expected to provide accurate assessments of vulnerability, but rather reasonable approximations to serve as a basis for comparisons of evolving concepts.

As the design process continues and the vehicle configuration matures, vulnerability considerations become more refined. The expertise of BRL in armor/anti-armor engineering is brought into play in order to make use of their extensive experience along both theoretical and experimental lines. The extent to which BRL can fulfill its responsibilities is largely a function of the adequacy of the technological data base it has established through research on both weapons effects (terminal ballistics) and armor performance.

ROLE OF LIVE-FIRE TESTING DURING DESIGN

Because the ability to analytically predict terminal ballistic effects lags behind new technological developments of ammunition and armor, empirical testing with live ammunition must remain an important basis for design evaluations. Therefore, it is important that adequate experiments, including the use of live ammunition, be conducted according to a carefully arranged plan that complements the design process. Particularly for those aspects of a system which represent a departure from past design practice and field experience, either in terms of vehicle design or nature of enemy weapons likely to be encountered in battle, the importance of appropriate and timely live-fire testing cannot be overemphasized.

The purpose of using live ammunition during the development and design phases is to provide *engineering information*, and the experiments should be designed with this objective in mind. Also, it should be kept in mind that, while firings against components can usually be accomplished relatively inexpensively and may have wide application to different vehicles, the cost and time needed to conduct live ammunition firings against subsystems and total systems escalate rapidly. Hence, firings against subsystems and total systems must be used in a balanced manner to help the designer reduce the uncertainty of achieving success in the final vehicle configuration.

Engineering tests and their manner of execution are governed by the need to obtain necessary information with the least expenditure of resources. In such tests, inert components may be substituted for live ammunition and fuel so as to simulate dynamic effects while preventing catastrophic damage to the vehicle. Data resulting from such tests should suffice to reach conclusions regarding such matters as blast effects, spall patterns, and damage to sensitive areas such as turret drives. It should be emphasized that engineering tests of this kind should be conducted in a different fashion than full-scale, combat-loaded, live-fire tests, which have a fundamentally different purpose.

3
Vulnerability Analyses

VULNERABILITY MODELING

How, then, is the vulnerability of vehicle X to weapon Y predicted? It should be evident at once that answers cannot be based wholly on live firings at full-scale, combat-loaded vehicles, since the number of experiments and vehicles required would be beyond reason in the case of a vehicle for which armor offers significant protection. Clearly, the approach must be made through a combination of analytical calculations supported by testing. With the availability of high-speed computers, several analytical approaches to vulnerability assessment have been developed at BRL and elsewhere. The approaches used by BRL will now be described briefly,[1] since they are representative of the techniques in use by other practitioners.

The roots of the analytical methods used in today's studies of armored vehicle vulnerability can be found in analyses of tests performed during the

[1] Deitz, P. H. and A. Ozolins. 1989. Computer Simulations of the Abrams Live-fire Field Testing. Memorandum Report BRL-MR-3755. Aberdeen Proving Ground, Md.: U.S. Army Ballistic Research Laboratory. (Also published in the Proceedings of the XXVII Army Operations Research Symposium held at Fort Lee, Virginia on October 12-13, 1988 under the sponsorship of the U.S. Army Training and Doctrine Command, Fort Monroe, Virginia.) Substantial portions of the descriptive material and the account of the historical development of the computer simulations presented in this chapter and in Appendix C have been taken with slight modifications from this source.

1950s. This period of vulnerability testing and analysis culminated in a set of firings performed in Canada in 1959, referred to as the CARDE trials.[2] Approximately 400 antitank rounds were fired against armored vehicles including the U.S. M-47 and M-48 tanks. Most of the shots were performed with 5-inch through 8-inch chemical energy (CE) rounds. The CARDE tests were fired against armored vehicles in varying degrees of completeness. These vehicles were not combat-loaded, although fuel and ammunition are major sources of behind-armor damage. The results of the tests were used by BRL to refine a model,[3] referred to as the "Compartment" model, which had been developed in the previous year from a group of tests performed between 1950 and 1954. This model related certain warhead parameters to M-, F-, and K-kills, as defined previously.

Until the onset of current combat-loaded live-fire test programs, the pre-CARDE and CARDE trials represented the largest collection of firings against armored vehicles. By 1960, approximately 1,400 firings with large munitions against heavy armored vehicles had taken place. In addition, full-scale firings were performed as BRL continued to update its vulnerability data base. Between 1963 and 1976 various full-scale tests were performed, including small shaped-charge warheads against armored personnel carriers (110 shots in 1964), high-explosive (HE) projectiles against tanks (228 shots in 1971), influence-fuzed mines against tanks (172 shots in 1973), 30mm GAU-8 munitions against tanks (153 hits in 1975), and large-caliber, depleted-uranium, kinetic-energy (KE) penetrators against tanks (6 shots in 1976).

In 1977 BRL performed an in-house study to determine the methods, experiments, and data bases needed to modernize its analytical procedures for assessing armored vehicle vulnerability. The XM1 main battle tank was in advanced development using modern armors never fired against in a combat-ready configuration. Although BRL was not able to obtain M1s for full-scale firing, a set of controlled combat-loaded firings was performed at the New Mexico Institute of Mining and Technology in Soccoro using obsolete M-48 tanks. KE warheads were fired and the results were used to extend the BRL vulnerability data base.

[2] Canadian Armament Research and Development Establishment, "Tripartite Anti-Tank Trials and Lethality Evaluation, Part I", November 1959

[3] A model is a simplified mathematical representation of a physical system. In use it is embodied in a computer code.

From the time of the Soccoro tests until 1983, the use of modern armors (special, spaced, ceramic, etc.) in U.S. vehicles increased. By this time the utility of the CARDE data (obsolete projectiles against monolithic armors) was of diminishing value. The Joint Live Fire (JLF) test program, chartered in 1984 as an OSD-sponsored and funded program, was started in recognition of the need for a modernization of the vulnerability data base and methods. It operates through the DOD Joint Technical Coordinating Groups (JTCG), principally those for Munitions Effectiveness (JTCG/ME) and Aircraft Survivability (JTCG/AS). The overall thrust of JLF is to evaluate combat systems that have already been fielded. To date, the types of systems that have been or are being tested include armored personnel carriers, tanks, fixed- and rotary-wing aircraft, and a wide variety of guided and unguided weapons.

Following the inception of JLF, and in the midst of a controversy regarding the vulnerability of the M2/M3 Bradley Fighting Vehicle, the Defense Authorization Act of fiscal year 1987 mandated Live-Fire Testing (LFT) to evaluate the performance of all important combat systems prior to their entering full-scale production. Two important series of tests took place against the M2/M3 Bradley class of fighting vehicles. The second series of tests (Phase II) were conducted to correct procedural shortfalls which were believed by some to have been present in the first series of tests (Phase I). BRL was given the task of predicting shot outcomes *before* the firings, as well as helping to assess the results of field tests. These predictions of expected results, when compared with the results of the shots, revealed the need to upgrade the model that was being used in the M2/M3 Bradley program. That model, called VAST, was one of the first of a number of ground-vehicle vulnerability assessment models of the point-burst class, in contrast to the Compartment model.

The Compartment model was originally based on the individual damage states observed from approximately 1,400 firings, as described earlier. For each shot the observed damage state was mapped to the related probability of F- or M-kill. Lumped-parameter curves—the damage correlation curves referred to above—were fitted to these data. The result was an expected value estimate for the specific munition/target combinations tested. Basically, the Compartment model is used in the following manner:

- Select a shotline to simulate the weapon trajectory.
- Check for exterior damage to the suspension system and gun tube.
- Determine whether the munition perforates the target exterior.

- If the weapon perforates, check to determine whether a K-kill occurs because the main penetrator impacts fuel or ammunition. Such impacts are assumed to result in fuel ignition or ammunition detonation.
- If the weapon penetrates, utilize the damage correlation curves to estimate the magnitude of M- and F-kills for each compartment breached. These include K-kills from fragments impacting munition.
- Combine the kill probabilities assuming independence and using the probabilistic "survivor rule."

This model is only as good as the data base, and has historically been based on firings of increasingly antiquated munition/target pairings. In a future effort, BRL plans to use the results of a point-burst model to upgrade variants of the Compartment model for various combinations of munitions and targets. BRL has defined a long-term requirement for the maintenance of this class of model. Many important vulnerability/lethality studies are required for targets and/or munitions for which detailed information is not available. This situation is encountered, for example, in the study of foreign armored vehicles for which knowledge is limited or in U.S. concept trade-off studies where only a preliminary design exists.

During the early 1970s, point-burst models (including VAST) were developed. The VAST model attempts to characterize the behind-armor residual penetration and the behind-armor debris environment. More complex than the Compartment model, point-burst models require a knowledge of detailed debris data for every warhead/armor pairing that will be considered in an analysis. Detailed information must be available to permit the user to estimate the equivalent thickness or density of all modeled components. Then, in the event that these components are hit by the penetrator or spall fragments, the model can indicate whether the component is penetrated and, if so, determine the residual mass and velocity of the penetrator or fragment. In addition, information must be available to determine whether the critical components of the target will be damaged by penetrators or fragments over a wide range of impact velocities and masses.

All classes of vulnerability models are based upon the interpretation of experimental data. In the case of the Compartment model, the data are obtained from full-scale firings. After curve-fitting, the predictions of the kill probabilities can be inferred, but only for the particular munition and target combinations tested. The model cannot accommodate changes in the target configuration to examine vulnerability reductions or other modifications. In addition, given the small number of full-scale firings, the results may contain large sampling errors. In the case of point-burst modeling, the vulnerability estimates are actually determined by aggregating the results of many tests of warhead/armor pairings as well as of components. Although the modeling can accommodate various target geometries without serious difficulty, an enormous amount of input data is required. Finally, in many cases data for warhead/armor pairings are insufficient, especially with regard to the behind-armor debris environment.

When the requirement arose for vulnerability modeling in conjunction with the M2/M3 Bradley live-fire testing, BRL analysts considered various model options. The Compartment model was rejected on the basis of a number of significant limitations:

- No full-scale, combat-loaded firings had ever been conducted against the M2/M3 Bradley Fighting Vehicle. Thus, there were no empirically based Compartment model damage correlation curves for this vehicle.
- Even if damage correlation curves had been available for a prior configuration of the M2/M3 Bradley, no parametric excursions from the system baseline would have been possible. For example, examining the effects of reconfiguring the location and shielding of interior components would have been precluded.
- The Compartment model does not predict component damage. Thus, it cannot produce results that are comparable with those of the live-fire tests.

At that time, BRL analysts concluded that the only available option was to utilize the VAST computer model. This model was used to make some 76 pre-shot predictions. Some of the important lessons learned are summarized below:

- The VAST predictions were compared with corresponding test results on a shot-by-shot basis. This was not a good basis for comparison because, as noted earlier, VAST, like all other vulnerability models available at that time, determines only expected (on the average) values. At the time, nothing was known about the probability density functions associated with M- and F-kills. Lack of appreciation for the possible variability of test results led to a widespread practice of comparing expected value output of the model to single outcomes from the live-fire tests.
- The M2/M3 Bradley tests showed that damaging a single, small component can dramatically affect system loss of function. In one case, the cutting of a single wire by an off-axis fragment resulted in a significant loss of firepower. This effect was not included in the calculations.

Thus, as BRL embarked on the M1 Abrams live-fire program, it was concluded that there was an immediate need for a stochastic point-burst model with the following characteristics:

• The geometric target modeling should be accomplished at an unprecedented level of detail.

• The vulnerability model should be capable of reflecting the chief forms of variability in the vulnerability assessment process that could lead to shot-by-shot variations in damage. This should include both variations in the causes of component damage given a hit and random (spatial) deflections of lethal fragments.

• The vulnerability model should compute damage states on a Monte Carlo basis so that probabilities of individual state outcomes could be assessed.

To meet the requirements of the M1 Abrams live-fire program, a totally new stochastic point-burst model was developed. Named SQuASH (for Stochastic Quantitative Analysis of System Hierarchies), this model was designed to accommodate expected threats including the special case of multiple hits from salvo-fired weapons. The model was designed to vary the following variables stochastically:

• Hit Point. Under the best conditions the geometric modeling of a complex target cannot reflect actual vehicles perfectly. In addition, actual vehicles of a particular type may vary with regard to wire routing, etc. Vulnerability models trace zero-width rays through the target to simulate possible projectile paths. This process considers only components that would be intercepted by the axis of the projectile and does not take into account the finite size of the projectile. To provide more realism, rather than using a single ray to model a striking projectile, a matrix of nine rays was chosen to provide sampling over a 6-inch cross section.

• Warhead Performance. Warhead performance is normally modeled in terms of the expected penetration capability. Repeated warhead/armor experiments using precision components have revealed random variations in depth of penetration and other parameters. The SQuASH model associates a distribution function with all warhead/armor computations, and random selections are made from this distribution function for each Monte Carlo iteration.

• Residual Penetrator Deflection. When kinetic energy projectiles impact armor at oblique angles, the residual portion of the penetrator can deflect upon armor exit. The deflection is greatest when the armor is just overmatched. A distribution function is used to select trajectories in the vicinity of the expected deflection.

• Spall Production. The VAST model treats spall by describing behind-armor debris in terms of fragment mass, velocity, and shape. Since much of this information is unavailable for many warhead/armor pairings in the M1A1 Abrams program, a spall treatment based on the concept of lethal fragments was used. For the past ten years, the United States has standardized spall data collection by using a package of thin metallic plates (witness plates). Lethal fragments are defined as those that penetrate at least the first witness plate. The SQuASH spall model describes the spatial density of lethal fragments as a bivariate Gaussian distribution and the expected number of fragments by a Poisson distribution. Using these two distributions and the size and location of critical components the number of lethal fragment impacts is determined.

• Component $P_{K/H}$ Characterization.[4] Each critical component in the target is separately characterized in terms of its probability of being killed by main penetrators and by single lethal spall fragments. For intermediate threats such as fragments from a shattered KE penetrator, intermediate kill probabilities are computed using hole size and penetration capability. Multiple hits are assessed using the "survivor rule."[5]

• Secondary Kill Phenomena. As mentioned earlier, the primary phenomena are often not adequately characterized, and even less is known about possible secondary effects. In general, secondary effects are not modeled by BRL analysts because they believe that these effects do not play a consistent and significant role in armored vehicle vulnerability assessments. Nevertheless, particular tests have been performed in which ballistic shock or blast have caused critical damage. In the M1 Abrams tank program there was insufficient time to introduce damage algorithms for these secondary phenomena. However, provisions were made in the model structure to support any additional damage algorithms that might be required.

[4] $P_{K/H}$ is defined as the probability of kill given a hit.

[5] The "survivor rule" is a mathematical expression for calculating the probability of survival for multiple hits, $P_s = (1 - P_{K/H})^n$, where P_s is the probability of survival, $P_{K/H}$ is the probability of kill given a hit for a single hit, and n is the number of multiple hits. The probability of kill for each of the hits is assumed to be the same.

Having considered the BRL VAST/SQuASH modeling approach in detail, and after much discussion among the members, it is the opinion of the committee that the elaborate detail incorporated in the BRL point-burst model to account for behind-armor effects tends to conceal the basic uncertainties that are inherent in the prediction of the vulnerability of armored vehicles. The result is an unjustified sense of the prediction's accuracy. In addition, the model's complexity makes it unsuited to respond rapidly to questions about the consequences of design changes. This limits its usefulness in the design process.

Rapid changes in penetrator and armor design are taking place. Behind-armor damage is known to be sensitive to the specifics of warhead or projectile performance. However, available intelligence is not able to accurately portray the performance of many current, as well as all future, threat weapons. Thus, even if there were no limit on behind-armor debris measurements that could be made in an experimental program, that would not overcome the uncertainty about the characteristics of the threat weapons. Furthermore, the present state of understanding concerning penetrator/armor interactions does not provide a satisfactory basis for predicting the consequences of variations from the threat munitions or surrogates used in the experimental program.

Also, very significant variations are observed in round-to-round results for ostensibly the same test conditions. It seems inappropriate, therefore, to focus on a model that requires detailed calculations for each penetrating fragment. It should also be recognized that the final vulnerability numbers that come out of the modeling include an assessment of how the vehicle damage affects the ability of the crew to carry out various missions. This is done by means of a Standard Damage Assessment List which is based on subjective judgments and is another argument for avoiding excessive detail in estimating damage. (The Standard Damage Assessment List is briefly discussed in Appendix C.)

These basic uncertainties limit the accuracy of the vulnerability estimates that can be obtained regardless of how much detail is incorporated in the model. At the same time, the use of the present modeling approach has other consequences which the committee believes to be undesirable. According to the information presented by the BRL there appear to be significant deficiencies in the experimental data base, not just for behind-armor debris but for penetration data as well. Too much emphasis on the collection of detailed behind-armor debris data for model-building purposes can impede the prosecution of a balanced terminal ballistics research program.

Finally, the committee believes the following considerations can simplify the assessment of damage from overmatching rounds without compromising usefulness or accuracy.

1. The exposure of critical components to the effects of penetrating rounds will vary with their general location in the tank. The precise location of these critical elements is not important in assessing the average vulnerability of the tank since thousands of possible shotlines must be considered in arriving at that assessment and since the behind-armor debris will be basically uncertain. A highly detailed description of the precise location of critical elements will not produce a better answer.

2. The damage sustained will obviously depend on the area intercepted by the behind-armor debris (in addition to the damage produced by the residual penetrator). Experiments are needed to establish the general characteristics of the spall, such as spall cone sizes and locations, for impacts penetrating the principal compartments of the tank. It is important to recognize that, even if the actual enemy weapons were available for tests, there would be no practical way to determine all of the possible variations in behind-armor debris resulting from complex weapons-armor interactions. Measurements made with witness plates provide the type of information needed, i.e., the distribution and penetrating power of the behind-armor debris.

3. Finally, the damage will depend on the hardness of the critical component and on its cross section, which determines the probability of its interception by behind-armor debris. Data are available on the vulnerability of various types of generic elements such as cables, fuel tanks, ammunition, crew, etc. Where there is uncertainty about the hardness of new components that are functionally critical, new test data must be obtained. The key components could be classified as either subject to functional damage or not subject to functional damage in the environment revealed by the witness plates. The cross sections of the components will then determine the probability of damage for components located in different areas of the tank.

An approach to modeling based on considerations such as these would also be useful in the early design phases and so could be helpful in evaluating design approaches intended to improve the protection against behind-armor debris. This could include an evaluation of the benefits of heavy armor protection for some critical components, relocation of critical components, and the possible benefits of redundancy in the design.

THE ARMOR/ANTI-ARMOR EXPERIMENTAL DATA BASE

Another area which the committee pursued is the adequacy of the armor/anti-armor data base. An adequate, state-of-the-art data base is essential to analysis of the vulnerability of U.S. combat vehicles to attack by enemy anti-armor weapons and essential to development of new vehicles.

The results of classified briefings given to committee members regarding armor performance relating to penetration data and behind-armor debris data are partially summarized in unclassified form in Tables 1 and 2. As the figures suggest, the performance of rolled homogeneous steel and aluminum armor against established anti-armor weapons is well documented. The situation with regard to all varieties of more advanced armor recipes and weapons is unsatisfactory.

The data are not only inadequate, but also fragmented and inconsistent. They are not organized into a single data base of consistent and comparable data, nor can they easily be so organized. Three factors leading to this situation are: (1) inadequate funds for data acquisition—such a program should be funded at a level several times the present level of less than \$6 million per year; (2) fragmented funding—over three-quarters of present funding comes through project managers who want tests run for their programs without attention to needs for comparability of data or cross-system analysis; and (3) compartmentalized information—the Army seems to be creating a separate security "compartment" for each new armor recipe and anti-armor weapon. The limitation of access has become so extreme as to preclude comparability of data and competent scientific peer review.

Based on the information available to it, the committee is of the opinion that the entire U.S. armor/anti-armor data base in general, and BRL's in particular, is lacking in both scope and depth. *It is essential that the data base be brought to, and maintained at, an acceptable level as rapidly as possible.* These data are prerequisite to understanding armor-warhead interactions and to improving designs for both attack and defense. In addition, without an adequate data base, the models for assessing vulnerability cannot provide meaningful information for analysis and engineering.

BRL should also provide a data base of ballistic effects on nonarmor components and subsystems installed in combat vehicles. The committee hopes that data of this kind will be collected during the design of specific vehicles. Although such data will probably not transfer directly from one generation to the next, the accumulation of experience will have generic value as its coverage increases.

TABLE 1 Status of Penetration Data

Armor Type	Warhead Type: Conventional Shaped Charge	Kinetic Energy Pentrators	Shaped Charge with Crossing Vol	Tandem Shaped Charges	Explosively Formed Penetrators
Homogeneous steel	3	3	3	3	3
Homogeneous aluminum	3	3	3	3	3
Spaced configurations of steel or aluminum	3	3	3	3	3
Laminates of steel and ceramics or plastics	1	1	1	1	1
Single element reactives	2	2	2	2	2
Multiple element reactives	1	1	1	1	1
Reactive appliques over steel/ceramic laminates	1	1	1	1	1
Special armor	3	3	3	3	3

Legend:
1 No analytical penetration models exist. Critical data voids exist.
2 Rudimentary models exist. Additional data are required.
3 Extensive data available. Additional data are of some importance.

Source: Rigotti, D. L., et al. 1988. Vulnerability/Lethality Assessment Capabilities--Status, Needs, Remedies. Special Publication BRL-SP-74. Aberdeen Proving Ground, Md.: U.S. Army Ballistic Research Laboratory.

TABLE 2 Status of Behind Armor Debris (BAD) Data

Armor Type	Warhead Type: Conventional Shaped Charge	Kinetic Energy Pentrators	Shaped Charge with Crossing Vol	Tandem Shaped Charges	Explosively Formed Penetrators
Homogeneous steel	3	2	1	1	3
Homogeneous aluminum	3	2	1	1	1
Spaced configurations of steel or aluminum	2	1	1	1	2
Laminates of steel and ceramics or plastics	1	1	1	1	1
Single element reactives	2	1	1	1	1
Multiple element reactives	1	1	1	1	1
Reactive appliques over steel/ceramic laminates	1	1	1	1	1
Special armor	2	2	1	1	1

Legend:
1 *No* analytical penetration models exist. Critical data voids exist.
2 Rudimentary models *exist*. Additional data are required.
3 Extensive data available. Additional data are *of* some importance.

Source: Rigotti, D. L., et al. 1988. Vulnerability/Lethality Assessment Capabilities--Status, Needs, Remedies. Special Publication BRL-SP-74. Aberdeen Proving Ground, Md.: U.S. Army Ballistic Research Laboratory.

4
The Role of Combat-loaded, Live-fire Tests in Vulnerability Assessment

Live-fire tests of full-scale, combat-loaded vehicles provide an independent check on the general success of the design and development process. The more successful the process, the fewer will be the surprises brought to light by the live firings.

Perhaps the best guide to the value of live-fire tests is the experience with the recent M1 Abrams and M2/M3 Bradley firings. The general conclusion reached by those who conducted and otherwise participated in the tests is that they were worthwhile, in that they disclosed design and operational changes which, when implemented, will reduce the vulnerability of the vehicles. These views were supported as well by the designers and users. Indeed, the user community indicated that they have learned the kinds of vulnerability information from the full-scale, combat-loaded, live-fire tests that they would expect to learn during the first few days, of combat.

The committee concludes that combat-loaded, live-fire tests serve the following functions:

- The tests conducted to date have identified important, unexpected vulnerabilities which were inadequately dealt with in the design process. Even the most careful design team will, at times, not recognize synergistic effects between subsystems and/or components which in turn produce negative vulnerability effects. During the course of tests, these may be brought to light.
- Although vulnerability is given careful consideration during the design process, the fact that live-fire tests, with their attendant high degree of visibility, will be conducted provides additional motivation to ensure that reduction of vulnerability is a top-priority objective.

• Live-fire testing provides the operational user community with a clearer perception of the vehicle's performance under fire. In the case of the M1 Abrams live-fire test series, the results led to changes in operational procedures and doctrine.

• The testing permits the realistic examination of Battle Damage and Repair (BDAR) techniques and time involved in returning combat-damaged vehicles to service.

• Finally, an ancillary benefit of the tests is that the results offer limited additional data and experience for the benefit of vehicle designers and model builders. However, *under no circumstances* should the design of the test series be influenced by this ancillary benefit.

The next question that arises in regard to the tests is: how much in the way of resources should be allocated to them? Combat-loaded tests are costly and time-consuming; estimates for the M1 Abrams and M2/M3 Bradley tests were on the order of $750,000-$1,000,000 per round fired, which includes planning, advance preparation, instrumentation, data reduction and analysis, and cost of vehicles. The total cost of the M1 Abrams and M2/M3 Bradley tests represent roughly one-third of 1 percent of the total acquisition cost of each system. These costs are comparable to those permitted by existing legislation, which has a limit of one-third of 1 percent of program acquisition cost.

The committee believes that future combat-loaded, live-fire tests need not cost this much per firing, particularly if an adequate program of engineering-test firings has already been completed during the development process. For example, some of the M1 Abrams and M2/M3 Bradley costs were incurred to support planning, installation, operation, and subsequent analysis of a very large number of instrumentation channels. This extensive level of instrumentation was justified by special requirements placed on the M1 Abrams and M2/M3 Bradley tests which are not, however, central to the effective conduct of combat-loaded, live-fire tests in the normal course of events. As an example, the potential toxicity hazards to the crew resulting from activation of the fire extinguishing system could have been studied equally effectively and much more economically during engineering-oriented tests.

The committee is of the opinion, therefore, that reductions in the cost per round can be achieved, and recommends further study of this matter. The instrumentation installed for combat-loaded, live-fire tests should be reduced to, and maintained at, a level commensurate with the specific objectives which the tests are intended to fulfill.

5
Selecting Live-fire Test Shots

Full-scale, combat-loaded, live-fire tests are intended to expose combat vehicles to an *unbiased* representation of the battlefield threat. In contrast to the purpose of tests designed to produce engineering data, discussed earlier in this report, combat-loaded, live-fire tests are intended to provide a random "snapshot" of the capacity of a new combat vehicle to fulfill its mission in the face of enemy fire.

This goal requires that the test series of firings be selected by a random process from the manifold possibilities which could be encountered on the battlefield. This philosophic approach is reflected in the following three-step process:

1. Develop the list of weapon-warhead combinations.
2. Determine the number of shots of each weapon-warhead combination to be fired.
3. Specify the parameters of each shot.

The approach to each step derives directly from the goals and context discussed in the preceding chapters. Note that the cost of the test program is much reduced if the safest shots, i.e., those anticipated to cause the least damage, are fired first.

DEVELOPING THE LIST

It is important that the list of weapon-warhead combinations be as complete as possible, including smaller weapons as well as larger ones and unconventional weapons as well as standard ones. As previously discussed, the tests are to determine with as little bias (whether due to preconceptions or other causes) as possible what happens when the vehicle is exposed to the full range of battlefield threats. Thus, while it would seem easy to exclude from the list rounds fired from an assault rifle, it would be unwise. For example, although omitted from live-fire tests of the M2/M3 Bradley Fighting Vehicle, incendiary rounds fired from an assault rifle can penetrate many aluminum armor recipes. Similarly one could include only high-explosive or kinetic-energy rounds fired from guns and thus incorrectly omit, for example, fuel-air explosives or unconventionally launched kinetic-energy weapons which could be equally serious threats.

DETERMINING THE NUMBER OF SHOTS

It should be noted that the complete test series can be viewed as a stratified random sample which, taking all shots together, gives an intuitive assessment of vulnerability performance. However, there is no probabilistic or statistical method, simple or sophisticated, that enables one to calculate precisely how many shots of which weapons should be fired to assure an adequate set of fully combat-loaded, live-fire tests. There are too many variables and too many unknowns. In spite of these difficulties, the committee observes that good experimental design practice dictates the following approach to arriving at the total number of shots and their allocation to specific weapon-warhead combinations.

A *minimum* of three shots should be fired for each weapon-warhead combination. This requirement establishes the minimum number of firings for the series. In the case of rapid-fire weapons, a shot should be considered to be a "standard burst." If no "standard burst" has been established for a rapid-fire weapon, then a burst of at least five rounds should be used.

For new systems incorporating substantial technological changes over past designs, the total number of shots in the combat-loaded, live-fire test series should be several times the minimum permissible number. A similar escalation of firings is justified when the nature of the threat has become significantly more critical than called for in the design ROC. In general, the greater the extent of design change over earlier practice and the degree to which the threat has intensified, the larger should be the total allocation of test firings.

Allocation of shots across weapon-warhead combinations should be based on an independent assessment of the likelihood of that weapon-warhead being used against the vehicle in the event of conflict when the vehicle is fielded, i.e., during the expected operational life of the vehicle. There is no simple formula for carrying out this task and no way to avoid some amount of subjective judgment. Thus, it is particularly important that the individuals charged with making these allocations be free to make their choices independently of both prior assessments and institutional pressures.

In determining the total number of shots actually to be fired, the experimental design should adjust for overmatching shots, which can be wasteful. However, as has been shown by recent tests, results can be pleasantly as well as unpleasantly surprising. Also, much can be learned from modestly overmatching shots. Thus, grossly overmatching shots, which will clearly be catastrophic in their effects, need not be fired, but modestly overmatching shots should be. An example of a grossly overmatching shot would be one in which a penetrating warhead with substantial remaining kinetic energy intersects a storage area containing sensitive ammunition. Such a shot, if fired, would clearly yield little information and expend a valuable vehicle that could have been used in future tests. Where such shots are not fired, they must be recorded in the protocol as K-kills conceded without test.

SPECIFYING THE PARAMETERS OF EACH SHOT

In a letter report submitted to Walter W. Hollis on October 20, 1986, the committee outlined a procedure for the random selection of shotlines. The following is a refinement and simplification of that approach.

For each firing of a weapon-warhead combination, the following parameters must be specified:

- point of impact on the vehicle,
- angle of attack of the shotline (in both the horizontal and vertical planes), and
- range.

The firings should be conducted at sufficiently close range to ensure that the warhead will strike the vehicle at the chosen impact point, trajectory direction, and velocity. To accomplish this with warheads whose damage potential is velocity sensitive, downloading of the propellant charge may be necessary to simulate longer ranges of engagement.

To minimize bias, each of these parameters should be selected randomly from an appropriately specified sample space distribution. The randomness should be achieved through use of tested lists of random numbers. Tables suitable for the random selections needed to carry out the selection procedures described here are maintained at BRL and are available for use by those designing a test series.[1]

Because many of the most important effects appear to be related to shots directed at the principal compartments of the vehicle, the committee recommends that for each weapon-warhead combination, successive shotline samples be drawn until at least one shotline selected is directed toward each of the main compartments. Note that the principal compartments for a tank are defined to include the crew and engine compartments and the turret region.

The specification of sample space distributions is somewhat different for three different directions of attack. The first is attack by weapons fired with relatively flat trajectories, that lie approximately in a horizontal plane. Examples are ground-to-ground attacks and attacks from low-flying aircraft at considerable range. The second is attack by weapons designed to damage the bottom of the vehicles, e.g., mines. The third is attack by weapons that approach at high-trajectory angles and are designed to strike the vehicle in its top region. An increasing number of weapons of this last type are entering the inventory.

Flat Trajectory Attacks

As already noted, for each round fired, it is necessary to specify by random selection the following parameters: (a) the direction of the shotline at the impact point on the vehicle, (b) the location of the impact point, and (c) the striking velocity. The procedure for accomplishing these parameter selections is essentially the same as that advanced earlier by the committee in a brief report submitted to Walter W. Hollis on October 20, 1986, and recommended for use in connection with the M2/M3 Bradley live-fire test series.

The procedure is as follows:

1. For reference purposes, establish an azimuthal coordinate in the horizontal plane with origin at the vehicle's center of gravity. The coordinate value (0°) corresponds to the straight ahead direction, and the range 0-180°

[1] In recommending the use of tables maintained by BRL as part of the shot selection process, it is assumed that the tables will be continuously updated and made more reliable, based on new information generated from Army-wide sources as it becomes available.

refers to the left-hand side of the vehicle (counterclockwise rotation) while 180-360° refers to the right-hand side.

2. The first objective is to establish the direction of the shotline on a horizontal plane. This is determined by a random selection from an appropriate BRL table of azimuthal coordinates. The BRL table is specific to each weapon and includes a weighting function which accounts for the probability that attacks on an enemy vehicle by that weapon will be variable around the 360° periphery. (For example, attacks by a main tank gun will in all probability be greater in the front region of a target vehicle than in the rear region.)

3. Having determined the direction of attack on a horizontal plane, it is necessary to consider attack directions which may be at a small elevation angle to the horizontal. The performance of some armor recipes may be sensitive to attack angle, hence the need to make this correction. (Small elevation angles may be caused by terrain variations, ballistic trajectory angles at impact, attacks on a vehicle by airborne flat-trajectory weapons, and the like.)

To account for this, make an equal probability random selection of elevation for -15°, 0°, and 15°. The combination of horizontal azimuthal angle and vertical angle defines the *direction* of the shotline.

4. Next, the *impact point* of the round and its *striking velocity* must be chosen. As a first step, the range at which the attacker fires at the vehicle must be chosen.

To accomplish this, make a random selection from a BRL table which incorporates a weighting function that takes into account the probability of engagement by the weapon in question at various ranges. (Note that the BRL tables make a distinction between "attack" and "defense" modes for certain attacking weapons. In an era of weapon systems capable of accurate fire on the move, the need for an engaged vehicle to be "parked," usually in a protected position, to enhance the accuracy of its firepower is eliminated and the distinction between "attack" and "defense" modes is no longer needed. Therefore, use only the BRL tables for "attack" mode.)

5. BRL also maintains ballistic tables for known threat weapons (or suitable U.S. surrogates) which describe the velocity characteristics along the trajectory of the round. For the range chosen in Step 4, the *impact velocity* on the combat vehicle is thus determined.

The dispersion characteristics represent probability distributions for the horizontal and vertical distances by which the warhead will depart from the aim point at various distances along the trajectory. Hence, from suitable BRL tables for random selections at appropriate range, choose at random a horizontal and a vertical dispersion. This will be used to move the point of impact away from the *aim point* (see Step 6).

6. According to usual firing doctrine, the *aim point* is the areal centroid (areal center of gravity) of the target as seen by the attacker. BRL computer graphics permit determination of this *aim point* when viewing the vehicular target from the shotline direction specified earlier. Using the horizontal and vertical dispersions determined in Step 5, displace the *aim point* by these amounts. This determines the *impact point* for the test firing.

7. The procedure described above leads to the determination of (a) shotline direction, (b) point of impact on the vehicle, and (c) striking velocity of the warhead. All of the parameters for the test firing are thus fixed.

Shotline selections are repeated as often as necessary to meet the requirements called for in the design of the test series.

Bottom Attack

Unless the characteristics of a particular mine are known, the detonation point should be assumed to be uniformly distributed on the bottom projection of the vehicle on the ground. Unless known to be otherwise, the angle of attack of a mine should automatically be set vertical. The range of the mine should be considered a uniform distribution between full dry ground clearance and expected clearance in soft ground in mildly hilly terrain.

Top Attack

Weapon systems designed to deliver warheads from above are just being introduced into the fielded inventory. They are usually of one of two types—unguided systems that deliver fragmentation warheads some distance above the top of the vehicle and guided systems that deliver a variety of warheads to the vehicle. While the committee has not worked through the detailed distributions from which the samples should be drawn, it is clear that this exercise can be done straightforwardly given adequate knowledge of the characteristics of the weapon-warhead systems.

6
Conclusions and Recommendations

1. A clear distinction must be made between (a) live firings conducted against fully combat-loaded vehicles, and (b) live firings conducted against vehicle components, subsystems, and prototypes during the course of engineering design and development.

   The latter tests are intended to provide engineering information at minimum cost and expenditure of resources. Combat-loaded, live-fire tests are for a different purpose, namely, to provide an independent check on the general success of the design and development process with regard to the vulnerability of the vehicle to enemy fire with threat weapons likely to be encountered on the battlefield.

2. The preparation of a ROC (Required Operational Capability) precedes the initiation of design and development of a new combat vehicle. All too often, the ROC underestimates the importance of emerging armor/anti-armor technologies. The result is that by the time the vehicle is ready to be fielded, the threat environment is more severe and perhaps even different in nature than that called for in the ROC. It is recommended that, as part of the design process, future designs allow for enhancement of ballistic protection during the vehicle's lifetime.

3. It is important that vulnerability assessments of combat vehicles be as dependable as possible. Not only are they important in defining the hazards to crew and vehicle, they are essential in assessing vehicle survivability on the battlefield, as well as for many other important Army planning purposes.

A complete description of the vulnerability of a vehicle is, however, a complex task. For each attacking weapon and warhead combination, the damage due to attack from all directions and at all ranges must be taken into account.

To arrive at vulnerability assessments, therefore, the only recourse is to make use of mathematical models capable of being executed on a high-speed computer, so that the damage due to large numbers of attacks can be assembled. Such models must be supported by an adequate base of data obtained experimentally by firings against armor samples, components, and subsystems.

4. Vulnerability models designed to at least two levels of comprehensiveness are required. For preliminary design purposes, a model is needed which provides relatively rapid estimates at an accuracy level sufficient to compare the relative advantages of competing concepts. At the opposite end of the spectrum, a more detailed model is needed for assessing the vulnerability of a design with best achievable accuracy.

   The committee has concluded that suitable models for addressing these needs are not currently available and further development is needed.

5. The committee has reviewed the current BRL approach to more accurate model building. It is, in essence, based on the belief that better accuracy will result from models of increasing detail, i.e., models that incorporate the vehicle exterior and interior geometry in relatively minute detail and that trace behind-armor damage virtually fragment by fragment. It is the committee's opinion that such an approach is not justified because of the inability to forecast with precision the characteristics and performance of ever-evolving threat weapons, and because of the inherently stochastic nature of penetration and behind-armor damage mechanisms. The trend toward increasingly detailed models is not a productive direction and the committee suggests that BRL reconsider its current direction for model design. A lesser degree of detail, using an approach based on a more generic assessment of the vulnerability of major components, would still provide valid vulnerability estimates with reduced data requirements and shorter computational times.

6. BRL is the Army's principal laboratory responsible for armor/anti-armor technology. Based on a review of the BRL data, encompassing unclassified as well as classified data, but not including sensitive compartmented information, it is evident that there is a significant lack of experimental information, particularly concerning the more sophisticated armor designs and anti-armor weapons representative of modern practice. A principal reason appears to be that in recent years the experimental work has tended to be conducted on an *ad hoc* basis for different development programs. The experimental research program that has been instituted to establish an integrated data base for use as a reference source for future designs and as a guide for formulating further research efforts has been neither coordinated nor comprehensive . The inadequacy of this experimental program is the largest single deficiency contributing to uncertainty in our current vulnerability estimates.

7. One purpose of this study is to better define the role of live-fire tests against fully combat-loaded prototype vehicles. It is important, therefore, to carefully delineate what functions these tests fulfill and, equally important, what they do *not* add to the process of vulnerability assessment.

   Specifically, combat-loaded, live-fire tests do *not* contribute significantly to the assessment of vulnerability in a form needed to support subsequent survivability assessments and for other necessary Army uses. The quantity of data gathered by such tests is too limited in scope and depth to be statistically significant.

8. Combat-loaded, live-fire tests will accomplish the following, provided the test series consists of randomly selected firings with shotlines selected by the procedure outlined in Chapter 5 or its equivalent:

   - During the interval between the start of the development and design process and the live-fire tests, the threat environment on the battlefield may have changed appreciably. Since the combat-loaded, live-fire tests are to be conducted with weapons constituting updated threat weapons, they provide some assessment of the vehicle performance with regard to vulnerability to weapons not incorporated in the ROC document.
   - The tests are conducted in an environment of high visibility within the Department of Defense, Congress, and, save for the limitations

of classified data, the public at large. Knowing that the test results will be carefully observed during the approval process leading to large-scale production, the program manager and his staff will be motivated to ensure that adequate weight is given to vulnerability considerations throughout the design process.

- The tests may uncover vulnerabilities that have not been anticipated and that represent design deficiencies. Experience to date has in fact shown that valuable information of this kind has emerged from combat-loaded, live-fire tests.

The results of combat-loaded, live-fire tests should not by themselves be construed as a basis for approval or disapproval of the transition to full-scale production. Many additional factors must be taken into account in arriving at this decision.

9. Combat-loaded, live-fire tests do not provide information of significant value for validating vulnerability models, although they may disclose vulnerabilities which have been overlooked in model formulations. The committee recommends that such tests should not be conducted with this purpose in mind.

10. Experience to date with combat-loaded, live-fire tests has indicated that they do produce positive findings helpful in reducing vehicle vulnerability. Many of the findings, however, could have been anticipated by more careful engineering testing conducted earlier and with substantially lower expenditure of resources.

11. To improve future design practices, and particularly to help less experienced designers without extensive "corporate" experience, the committee recommends preparation of a manual of good design practices for combat vehicles to reduce the vulnerability to penetrating rounds. Reflecting a compilation of sound design rules, as well as practices to be avoided, such a manual will help to prevent future mistakes that might result in increased vulnerability.

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Appendix A
Statement of Task

The Committee on a Review of Army Vulnerability Assessment Methods of the Board on Army Science and Technology will conduct an in-depth study of the methodology used by the Army for combat vehicle vulnerability assessment. This methodology attempts to provide a realistic estimate of combat damage to vehicle, equipment, and personnel sustained as the result of direct hits by hostile weapons. However, neither the Army, the Department of Defense, nor the Congress is satisfied that the current approach and the level of funding available to this program are adequate to yield an estimate of acceptable reliability.

The committee will conduct a review independently of the Army's in-house laboratories and contractors to: (a) address issues that will help the Army define the objectives of its vulnerability assessment program, (b) define and analyze alternative ways to balance computation and live-fire testing in reaching conclusions about vehicle vulnerability, (c) identify technical deficiencies where they exist, and (d) suggest alternatives for improvement as appropriate.

Appendix B
Schedule of Visits and Related Contacts

During the conduct of its study, the Committee on a Review of Army Vulnerability Assessment Methods held one of its regular meetings at each of the following locations, where it received in-depth briefings concerning the vulnerability question in terms of the appropriate resident activities.

• Ballistic Research Laboratory (BRL) Aberdeen Proving Ground, Maryland	January 28-29,1988
• U.S. Army Tank-Automotive Command (TACOM)[1] Warren, Michigan	March 2-3,1988
• U.S. Army Armor Center and Fort Knox Fort Knox, Kentucky	April 19-20, 1988

The following additional visits or contacts to conduct detailed discussions on specific, relevant issues were made by individual members or groups of members on behalf of the committee:

[1] At this meeting the committee also met with Brigadier General Peter M. McVey, Program Executive Officer Close Combat Vehicles, who is located at TACOM, and visited the nearby offices and plant of the General Dynamics Land Systems Division, which produces combat vehicles for the Army.

• On July 27, 1988, Arthur Stein and Charles Smith visited Dr. Wesley Kitchens and selected members of his staff at the Terminal Ballistics Division, BRL to discuss various experimental research and development programs relevant to the issue of combat vehicle vulnerability assessment. Later on the same day these members discussed the conduct of live-fire tests and the interpretation of the results with Dr. Lawrence Kravitz of the Army Materiel Systems Analysis Activity (AMSAA), which is also located at the Aberdeen Proving Ground.

• On August 2, 1988, at the request of Martin Goland, Ralph Cooper contacted Dr. Gary Holloway, Director of the Live-Fire Test Office at the U.S. Army Test and Evaluation Command (TECOM), Aberdeen Proving Ground, to obtain information on the average cost per shot of the live-fire testing of the M1 Abrams Tank and the M2/M3 Bradley Fighting Vehicle.

• On August 3, 1988, Donald Cudney visited D. L. Rigotti and selected members of his staff at the Vulnerability/Lethality Division, BRL, to discuss various aspects of computer models of the live-fire testing of combat vehicles.

• On October 10, 1988, Martin Goland visited James O'Bryon, Director, Live-Fire Testing, Office of the Under Secretary of Defense for Acquisition, to discuss the live-fire testing program.

Appendix C
Standard Damage Assessment List

Following the pre-CARDE trials, which were carried out in the 1950s, a mapping artifice called the Standard Damage Assessment List (SDAL) was developed. The SDAL is a listing of approximately 120 major systems and components which compose an armored fighting vehicle. Later modified by a board of Army officers and armor specialists, it represents their best estimates of the relative combat utility (CU) of a vehicle given the loss of each specified system, component, or group of components. These estimates assume all possible combat scenarios, both offense and defense, and tank doctrine as then promulgated. The accepted practice has been to equate the decrement in combat utility (DCU, the complement of CU) with a probability of kill. It has been recognized for some time that this methodology has serious flaws from both a mathematical and an implementation standpoint. For example, it is clear that the decrement in combat utility (e.g., the firepower function is 80 percent of that for an undamaged vehicle) is not the same as a probability function (e.g., 80 percent of the time the firepower function will not be affected). Some analysts have dropped the label "probability of kill" in favor of "expected loss-of-function" for the M and F variables; however, users of these vulnerability estimates continue to use them as probabilities. Nevertheless, because modern tanks have many critical systems and components which were not part of the original SDAL, other vulnerability analysts have generated an updated SDAL, under the auspices of the Chicken Little Program, which was initiated in the mid-1980s and is still active. Offense and defense scenarios were examined separately as well as averaged, and mission-dependent kill criteria were defined. For the first time, the framework for this process was documented.

However, the BRL has deferred adoption of the new SDAL values in favor of attempting to define new sets of kill definitions that are both consistent and directly relatable to field damage states. AMSAA is assisting the BRL in accomplishing these objectives.

Every point-burst analysis code requires that a criticality analysis be performed. A criticality analysis of a target involves a two-step process. First, every component of the vehicle which supports the M or F function must be identified. Second, the logical interconnectivity of each component in its respective system or subsystem must be represented in a deactivation diagram which is a form of fault-tree analysis. By this process, the potential loss of a component on a given system function can be assessed so that the SDAL can be invoked in the mapping process.